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Deep Borehole Disposal Remediation Costs for Off-Normal Outcomes

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This memo describes rough-order-of-magnitude (ROM) cost estimates for a set of off-normal (accident) scenarios, as defined for two waste package emplacement method options for deep borehole disposal: drill-string and wireline. It summarizes the different scenarios and the assumptions made for each, with respect to fishing, decontamination, remediation, etc.

Description of the emplacement method options comes from *Handling and Emplacement Options for Deep Borehole Disposal Conceptual Design* (Cochran and Hardin 2015). Costs for normal operations are consistent with *Waste Package Emplacement Cost Estimates for Deep Borehole Disposal* (Hardin 2015). The intended use of cost information is a conceptual design study with the principal objective of recommending one of the emplacement methods based on cost-risk analysis.

Costs are estimated for accidents that occur only during waste emplacement in a single borehole (and not during drilling and construction, setting cement plugs during emplacement, and final sealing of the borehole). These costs are for special operations subsequent to accidents, identified as five scenarios A through E, plus three more related cases (Table 1). The estimates do not include costs that would occur with normal operations such as sealing and plugging the disposal borehole, and de-mobilization.

Estimated costs range over more than an order of magnitude depending on whether waste package breach is detected, leading to decontamination and disposal of contaminated fluids, drill rig, and other equipement. Regulatory delay of either 1 or 2 years is also incorporated after an accident depending on whether breach has been detected.

Off-Normal Outcomes

Outcome A – One or more waste packages (WPs) is breached above the emplacement zone (EZ), i.e., above approximately 3 km depth. Breach is defined as detection of anomalous radiation downhole (e.g., gamma tool in wireline tool string or drill-string instrumentation package), or in mud returns. Once a radiation leak has been verified, all operations will come to a complete stop with no further insertion or withdrawal of tools in or from the borehole, and no borehole fluid circulation. Complete stop is necessary to protect rig workers, because it is assumed that decontamination and radioactive waste management facilities are not yet available at the site.

It is assumed that no additional WPs will be emplaced in a borehole after breach, that activities will focus on stabilizing the spread of contamination at the surface and in the subsurface, retrieval of waste from above the EZ, sealing and plugging of the borehole, and management of the low-level waste (LLW) accumulated at the surface.

One of the first activities after breach is detected will be purchase of all rented equipment by the operator because contamination is very likely if it has not occured already. This will decrease or eliminate standby charges during remediation planning. It is assumed that purchase provisions, in the event of a verified radiation leak downhole, are incorporated into all equipment contracts. Estimated costs for writeoff of the drill rig and related equipment, or writeoff of a wireline truck and coiled-tubing rig, are \$30M and \$20M, respectively. These costs are uncertain and could vary from \$15M to \$50M.

Once the equipment is operator-owned, a skeleton crew will maintain it in operable condition and maintain site security. All equipment on site including any drill rig, mud and cement handling equipment, wireline truck, and/or coiled-tubing rig, is assumed to be contaminated at this point such that it cannot be moved. Eventually it will be used for fishing, pulling casing, sealing and plugging activities, during which it is likely to become further contaminated. Ultimately it will be decontaminated and disposed of as LLW.

After a 2-year delay for regulatory review and remediation planning, response facilities will be built (Appendix A), and fishing operations will be conducted to retrieve the WP(s) to surface. If wireline emplacement was in use when the WPs became stuck, the wireline will be detached and retrieved, and a drill rig mobilized to the site. If drill-string emplacement was in use, the drill string will be withdrawn, decontaminated, stored temporarily, and used for fishing. If withdrawal is not possible, the string will be removed in sections. Fishing duration of 20 days is assumed because successful fishing will likely be accomplished in this time frame (and increasingly likely to be unsuccessful if protracted).

Borehole fluid (i.e.,"emplacement mud") will be circulated out of the hole during fishing operations. It is assumed that 3 hole volumes, plus the original volume, will be circulated and stored at the surface (totaling 3,400 m^3; see Appendix A) to remove subsurface contamination to the extent possible.

The outcome then differs according to whether fishing successfully removes WPs stuck above the EZ (A1) or fishing fails and one or more WPs are left in place (A2) (Table 1). In both cases incremental costs are incurred for fishing, building and operating radiological response facilities, LLW management, disposal of the drill rig and related equipment, loss of disposal borehole capacity, and long-term site monitoring (100 years). If WPs are recovered they will be decontaminated to the extent possible, inspected, and shipped back to the point of origin for remediation. If fishing fails, an additional delay of 1 year is assumed for regulatory review, then the borehole will be sealed and plugged (following a modified plan).

A requirement is assumed for long-term monitoring at the site for at least 100 years, whether or not the stuck WPs are successfully fished, because of the radiological release. This cost could include monitoring wells and periodic sampling. The 100-year time horizon is selected for this study. Monitoring, well pumping, and other activities could extend beyond 100 years depending on site-specific factors.

Outcome B – One or more WPs is breached within the EZ. As described above, once a radiation leak has been verified all operations will come to a complete stop with no further insertion or withdrawal of tools in or from the borehole, and no borehole fluid circulation. It is assumed that no additional WPs will be emplaced in a borehole after breach, that activities will focus on stabilizing the spread of contamination at the surface and in the subsurface, sealing and plugging of the borehole, and management of the low-level waste (LLW) accumulated at the surface.

As noted above one of the first activities after breach is detected will be purchase of all rented equipment by the operator, using purchase provisions incorporated into all equipment contracts. Estimated costs for writeoff of the drill rig and related equipment, or writeoff of a wireline truck and coiled-tubing rig, are \$30M and \$20M, respectively. Once the equipment is operator-owned, a skeleton crew will maintain it in operable condition and maintain site security.

All equipment on site including any drill rig, mud and cement handling equipment, wireline truck, and/or coiled-tubing rig, is assumed to be contaminated at this point such that it cannot be moved. Eventually it will be used for sealing and plugging activities, during which it is likely to become further contaminated. Ultimately it will be decontaminated and disposed of as LLW.

After a 2-year delay for regulatory review and remediation planning, response facilities will be built (Appendix A), and borehole fluid (i.e.,"emplacement mud") will be circulated out of the hole (totaling 3,400 m^3) to remove subsurface contamination to the extent possible. The borehole will then be sealed and plugged (following a modified plan).

A requirement is assumed for long-term monitoring at the site for at least 100 years, which could include monitoring wells and periodic sampling. The 100-year time horizon is selected for this study. Monitoring, well pumping, and other activities could extend beyond 100 years depending on site-specific factors.

Outcome C – Waste packages are dropped and come to rest intact unbreached within the EZ. A radiological survey will be conducted to verify the unbreached condition of the WPs, using either a wireline tool run within drill pipe (for drill-string emplacement), or a detector that is part of the wireline tool string (wireline emplacement). The outcome differs as to whether junk (either drill pipe or wireline, depending on emplacement method) is dropped on top of them (C2) or not (C1).

After 1 year of replanning and regulatory review, if the WPs are free of junk then a cement plug will be installed and emplacement will continue (C1). No loss of disposal capacity is assumed.

Any junk present (C2) will be fished using a drill rig. For drill-string emplacement operations, the same rig will be used. For wireline operations, a rig will be mobilized to the site then de-mobilized when fishing is complete. Fishing will be performed with moderation so as not to breach WPs, and junk may be left in the hole if appropriate. Fishing duration of 20 days is assumed because successful fishing will likely be accomplished in this time frame. A cement plug will then be installed and emplacement will continue. Any WPs fished from the hole because they are attached to large pieces of junk, will be inspected and shipped back to the point of origin for remediation. For costing it is assumed that only one WP is recovered during fishing.

Outcome D – One or more WPs becomes stuck in the EZ during emplacement. A radiological survey will be conducted to verify the unbreached condition of the WPs, using either a wireline tool run within drill pipe (for drill-string emplacement), or a detector that is part of the wireline tool string (wireline emplacement). The wireline or drill string will then be detached and withdrawn. The drill string will not be used to push down on waste packages (to free them) because they are already located in the EZ, and because there will be no further emplacement in any borehole where stuck conditions occur.

The drill rig and associated equipment, or the wireline and coiled-tubing rigs and their associated equipment, will be de-mobilized during replanning as a cost-saving measure. Although keeping a rig on site during replanning and regulatory review could help stabilize the stuck WPs, for costing it is assumed that they are setting on the bottom (i.e., at total depth, or on a cement plug). After a 1-year delay for replanning and regulatory review, a workover rig will be mobilized to the site. The EZ below the stuck WP(s) will be cemented to the extent possible, then the borehole will be sealed and plugged. These cementing, sealing, and plugging activities (including casing removal) are within the scope of normal operations and are not costed here (Hardin 2015).

Outcome E –One or more unbreached WPs is stuck above the EZ. WPs stuck using drill-string emplacement are assumed to be stuck in full connected strings. A radiological survey will be conducted to verify the unbreached condition of the WPs, using either a wireline tool run within drill pipe (for drill-string emplacement), or a detector that is part of the wireline tool string (wireline emplacement).

For wireline emplacement operations, the wireline will then be detached and withdrawn, and a drill rig will be mobilized to the site. For both drill-string and wireline operations, the drill rig will be used with drill pipe to stabilize the fish to the extent possible, to reduce the likelihood that the WP(s) will fall. The drill string will not be used to push down on the fish because that could push WPs through and drop them to the bottom.

After a 1-year delay for regulatory review and remediation planning, fishing operations will be conducted to retrieve the WP(s) to surface. Fishing duration of 20 days is assumed because successful fishing will likely be accomplished in this time frame (and increasingly likely to be unsuccessful if protracted).

The outcome then differs according to whether fishing successfully removes WPs stuck above the EZ (A1) or fishing fails and one or more WPs are left in place (E2) (Table 1). In both cases incremental costs are incurred for fishing and loss of disposal borehole capacity. If WPs are recovered they will be decontaminated to the extent possible, inspected, and shipped back to the point of origin for remediation.

If fishing fails (E2) an additional delay of 1 year is assumed for regulatory review, then the borehole will be sealed and plugged (following a modified plan). Costs will include long-term site monitoring (100 years) which could include monitoring wells and periodic sampling. The 100-year time horizon is selected for this study. Monitoring, well pumping, and other activities could extend beyond 100 years depending on site-specific factors.

Cost Estimates

Estimated costs (Tables 2 and 3) range from a few millions (Outcomes C1 & C2) to more than $300M (Outcomes A1, A2 & and B). The most important cost driver is WP breach with contamination of the borehole and surface equipment. The costs for radiological response and LLW management are detailed further in Appendix A. The next most important cost driver is leaving WP(s) above the EZ, with the expense of failed fishing, and the requirement for long-term monitoring. Another driver is rig standby time where it cannot be avoided, for example, stabilizing WP(s) stuck above the EZ.

References

Cochran, J. and E. Hardin 2015. *Handling and Emplacement Options for Deep Borehole Disposal Conceptual Design*. SAND2015-6218. Albuquerque, NM: Sandia National Laboratories.

Hardin, E. 2015. Waste Package *Emplacement Cost Estimates for Deep Borehole Disposal*. SAND2015-6372 O. Sandia National Laboratories, Albuquerque, NM.

Jenni, K. and E. Hardin 2015 (draft). *Methodology for Evaluating and Comparing Emplacement Options for Deep Borehole Disposal Conceptual Design*. Rev. 2.

Table 1. Off-normal outcomes for drill-string or wireline emplacement (from Jenni and Hardin 2015, Table 2).

Outcome		Additional assumptions	Performance metrics: Occupational safety	Performance metrics: Detectible radiation levels in borehole	Performance metrics: Incremental cost of emplacement operations (over costs for normal operations, wireline)	Performance metrics: Time to emplace 400 WPs
A *A1 =* *A2 =*	Breached WP(s) stuck above emplacement zone *Successfully fished* *Left in place*	Borehole is either: 1) decontaminated, sealed and plugged after WP(s) is removed (*A1*); or 2) decontaminated to the extent possible, sealed/plugged and monitored with WP(s) in place (*A2*).	To be discussed with expert panel and data, estimates, or assumptions developed as necessary. Primary occupational risk may be risk of radiological exposures if servicing emplacement equipment	Yes	For *A1*, include fishing, decontamination, LLW management, incremental costs to seal and close in a contaminated environment, and loss of disposal capacity. For *A2* add costs for long-term (100-year) monitoring.	Incremental time equal to the downtime to implement each solution. To be developed
B	Breached WP(s) in emplacement zone	Borehole decontaminated, and completely sealed and plugged with WP(s) in place.		Yes	Fishing, decontamination, LLW management, incremental costs to seal and close in a contaminated environment, loss of remaining disposal capacity.	
C *C1 =* *C2 =*	WP(s) dropped into emplacement zone unbreached, or junk dropped onto emplaced WP(s) which remain unbreached *Only WP(s) dropped* *WP(s) dropped with drill string attached, or drill string dropped onto WP(s)*	Unbreached packages will be left in place and the disposal interval sealed/plugged (*C1*), unless dropped while connected to a drill string (*C2*). Dropped drill pipe (junk) will be removed, and packages also if they are attached. (Retrieved packages will be tested/repackaged). The borehole remains suitable for emplacement of additional wastes.		No	Delay and loss of disposal capacity if a disposal interval is not filled (*C1*). For *C2* add fishing costs for drill string and any attached WPs.	
D	Unbreached WP(s) stuck in emplacement zone	No fishing; borehole sealed/plugged above stuck package; emplacement continues above seal/plug.		No	Delay, loss of disposal capacity.	
E *E1 =* *E2 =*	Unbreached WP(s) stuck above emplacement zone *Successfully fished* *Left in place*	Borehole is either: 1) sealed and closed after package is removed (*E1*); or 2) sealed, plugged, and monitored with package(s) in place (*E2*).		No	Delay, fishing costs, and loss of disposal capacity (*E1*). For *E2* add costs for long-term (100-year) monitoring.	
F. Normal operations, emplacement of 400 WPs						
F1	Drill-string emplacement		See above	Normal operations would not lead to radiological release or exposure	~$17.4 million (differential)	430 to 470 days
F2	Wireline emplacement				0	

Table 2. Estimated costs for off-normal outcomes of deep borehole waste emplacement.

Incremental Costs for Off-Normal Outcomes	Normal rig day rate		$ 75,000	$/day	
(See Methodology Report, Table 2)	Standby rig rate		$ 30,000	$/day	
	Fishing rate		$ 5,000	$/day	
	Owned rig maint. rate		$ 5,000	$/day	
	# WPs per wireline run		$ 1		
	# WPs per string (DS)		40		
	Drill-String		**Wireline**		
Outcomes	**Days**	**Cost**	**Days**	**Cost**	**Notes**
A1: WP(s) breached above EZ; WP fished; hole plugged and sealed; all equipment discarded; site decontaminated					
Drill rig or wireline/coiled tubing rig write-offs		$ 30,000,000		$ 20,000,000	Implement early for drill-string mode; could range from $15-50 M
Standby maintenance of operator-owned equipment	730	$ 3,650,000	730	$ 3,650,000	
Fishing	20	$ 1,600,000	20	$ 1,600,000	
Build response facilities		$ 116,000,000		$ 116,000,000	
Response operations		$ 46,000,000		$ 46,000,000	
Waste management		$ 52,000,000		$ 52,000,000	
Handle and remediate WPs fished from borehole		$ 20,000,000		$ 500,000	Assume 40 WPs per drill-string emplacement; one for wireline
Loss of disposal capacity		$ 20,000,000		$ 20,000,000	Expected loss is half of new borehole cost ~$40M
Long-term site monitoring		$ 36,000,000		$ 36,000,000	
Outcome A1 incremental cost		**$ 325,250,000**		**$ 295,750,000**	
A2: As above but one or more WPs not fished but left in place above EZ.					
Long-term site monitoring		$ 36,000,000		$ 36,000,000	
Additional standby	365	$ 1,825,000	365	$ 1,825,000	
Credit packages not recovered or requiring remediation		$ (20,000,000)		$ (500,000)	Assume that all packages remain stuck and are left in place
Outcome A2 incremental cost		**$ 343,075,000**		**$ 333,075,000**	
B: WP(s) breached within EZ; no fishing; hole plugged and sealed; equipment discarded; site decontaminated.					
Standby	730	$ 3,650,000			Maintain owned rig in place during response planning
Build response facilities		$ 116,000,000		$ 116,000,000	
Response operations		$ 46,000,000		$ 46,000,000	
Waste management		$ 52,000,000		$ 52,000,000	
Drill rig write-off		$ 30,000,000		$ 20,000,000	Implement early for drill-string mode; could range from $15-50 M
Loss of disposal capacity		$ 20,000,000		$ 20,000,000	Expected loss is half of new borehole cost ~$40M
Long-term site monitoring		$ 36,000,000		$ 36,000,000	
Outcome B incremental cost		**$ 303,650,000**		**$ 290,000,000**	
C1: WP(s) dropped into EZ (without drill pipe or wireline); no breach; cement interval; continue emplacement.					
Standby	365	$ 10,950,000	365	$ 10,950,000	
Loss of disposal capacity		$ -		$ -	Assume no loss of disposal capacity
Outcome C1 incremental cost		**$ 10,950,000**		**$ 10,950,000**	
C2: Junk (drill pipe or wireline) on top of WPs in EZ; no breach; fish junk and packages if attached; continue emplacement.					
Rig mob./demob.				$ 1,000,000	Use special rig for fishing wireline, then de-mob.
Fishing	20	$ 1,600,000	20	$ 1,600,000	
Standby	365	$ 10,950,000			
Handle and remediate WPs fished from borehole		$ 500,000		$ 500,000	Assume one waste package is recovered during fishing
Loss of disposal capacity		$ -		$ -	Assume minor loss of disposal capacity
Outcome C2 incremental cost		**$ 13,050,000**		**$ 3,100,000**	
D: WP stuck in EZ; no breach; no fishing; cement up entire EZ; complete borehole sealing/plugging; no more disposal in this borehole.					
Standby (de-mob/mob rig)		$ 1,000,000		$ 1,000,000	
Loss of disposal capacity		$ 20,000,000		$ 20,000,000	Expected loss is half of new borehole cost ~$40M
Outcome D incremental cost		**$ 21,000,000**		**$ 21,000,000**	
E1: WP stuck above EZ; fished successfully; no breach; cement EZ and complete borehole sealing/plugging; no more disposal in this borehole.					
Fishing	20	$ 1,600,000	20	$ 1,600,000	
Standby (incl. de-mob/mob rig)	365	$ 10,950,000	365	$ 10,950,000	Drill rig mobilized WPs stuck using wireline (use standby rate)
Handle and remediate WPs fished from borehole		$ 20,000,000		$ 500,000	Assume 40 WPs per drill-string emplacement; one for wireline
Loss of disposal capacity		$ 20,000,000		$ 20,000,000	Expected loss is half of new borehole cost ~$40M
Outcome E1 incremental cost		**$ 52,550,000**		**$ 33,050,000**	
E2: As above but one or more WPs not fished but left in place above EZ.					
Long-term site monitoring		$ 36,000,000		$ 36,000,000	
Additional standby	365	$ 10,950,000	365	$ 10,950,000	
Outcome E2 incremental cost		**$ 99,500,000**		**$ 80,000,000**	
F: Normal emplacement		$ 17,400,000		$ -	Incremental cost shown is for normal operations

Appendix A. Rough Scope/Cost Estimate for Outcomes Involving Breached Waste Packages

Boundaries of Analysis:

- During emplacement operations waste package is breached
- The package breaches at 16,000 ft depth
- The reason for the breach is not relevant to the analysis
- Downhole closure operations (e.g., borehole sealing) are not included

Assumptions:

- Waste form is Cs/Sr capsules .
- Eight Cs-137 capsules release their contents to the mud-filled borehole.
- Each capsule contains 37.5 KCi of Cs-137 (300 KCi total for 8 capsules.
- Randklev presentation to Nuclear Waste Technical Review Board (June 15, 1994) decayed to 2020 gives 50 MCi for all 1332 Cs-137 capsules.
- Due to high gamma radiation from Cs-137, many operations must be in shielded facilities and operated remotely.
- Due to transferrable contamination (if contaminated mud dries), many waste management (WM) operations must be in negative-pressure HEPA filtered facilities.
- Due to transferrable contamination, personnel working inside negative-pressure building in respirators .
- Assume original mud volume, plus 3 additional volumes are circulated to remove Cs from borehole (850 x 4 = 3400 m^3).
- Assume 95% of Cs removed by mud circulation, 5% remains in borehole .
- Assume solidification increases volume of mud by 33% (total solidified mud volume ~4,500 m^3).
- Average specific activity of cesium in solidified mud: 300 kCi/4500 m^3 x 0.95 = 63 Ci/m^3.
- Solidified drilling mud (at 63 Ci/m^3) would be Class C LLW at generation.
- Assume 100 m^3 for pulled casing
- Volume of personal protective equipment is 5% of total volume
- Volume of waste from decommissioning of facilities assumed as 25% of total volume and will be Class A LLW
- Assume borehole location is several hours drive from major city

Other Inputs:

- Mud volume is ~ 850 m^3 (22” to 1500 m and 16” from 1500 to 5000 m)
- 4.5” drill pipe has volume of 52 m^3 for 5 km of pipe (18,000 lb/m^3)
- Squeegeed casing and drill pipe will be Class A LLW
- Drill rig weight is equivalent to 135 m^3 of steel
- Very limited contamination of drill rig – possibly disposed in industrial landfills as allowed under 10 CFR 20.2002.

Facts about Cs-137:

- Managed as gamma-emitter (Cs-137 (half-life 30.2 years) decays by beta to Ba-137 (half-life ~2 minuntes) which decays by gamma
- Rule of thumb dose rate: 0.33 rem/hour/Ci at 1 meter (from direct gamma, inhalation dose will be much higher)
- Highly soluble in water as chloride salt or melt

Overview of Response Actions:

- Release of Cs-137 will be detected in downhole detectors (wireline or drill-string instrumentation) or mud handling equipment
- All operations stop
- EOC engaged
- Mud handling equipment enclosed in high-density polyethylene, personnel surveyed, etc.
- Response & Closure Plan written, approved – 1 year required plus additional regulatory review
- Build facilities and equipment listed below
- Conduct on-site response and recover operations
- Ship wastes off-site
- Decommission site infrastructure
- Ship decommissioning wastes off-site
- Implement long-term site monitoring program

Response Facilities:

1. Facilities for Management & Personnel – Additional portable buildings for operations management, HP, industrial safety, response personnel, storage, etc.
2. Facilities for Managing Contaminated Mud
    a. Remote controlled, mud handling system inside a shielded hot cell, that is inside a building with negative pressure. Four shielded tanks for mud storage.
    b. Remote controlled & shielded WM facilities to solidify contaminated mud in 1 m3 containers, includes shielded storage area for 4,500 one-m3 containers
3. Facilities for Managing Contaminated Drill Pipe and Casing
    a. Remote controlled, drill pipe and casing handling system inside a shielded hot cell, that is inside a structure with negative pressure, to pull, coat with fixative and cut drill pipe and casing to 3-m lengths, which are stored in 15 m3 boxes
    b. Storage building for storage of packaged drill pipe and casing
4. 4. Drill Rig Management
    a. Building for long-term storage of packaged drill rig

Response Operations:

- Staffing:
    - Response management & support personnel: 11 people
        - Project management (1)
        - Health physics (2)
        - Industrial safety (2)

    - Security (5)
    - Project controls (1)
  - Response personnel, both drillers and WM personnel: 15 people
- Training and qualifications, procedures, quality assurance, cold test of operations, repairs, etc.
- With shielded, remote-controlled equipment, circulate fresh mud to reduce contamination in borehole; assume 4 borehole volumes of mud (3400 m^3 total); store in four shielded tanks
- With shielded, remote-controlled equipment, solidify drilling mud with solidification agent; store solid mud in 1 m^3 containers; adds 33% to volume giving ~4500 m^3; store the 4500 containers
- Use contaminated drill pipe to seal and close borehole (not costed)
- With shielded, remote-controlled equipment, pull contaminated casing, wipe it down, decontaminate, coat with fixative, and cut into 3-m long sections
- With shielded, remote-controlled equipment, pull contaminated drill pipe, wipe it down, decontaminate, coat with fixative, cut into sections 3 m long, store in 15 m^3 boxes
- Disassemble drill rig, cut drill rig into sections 3-m long; store in roll-offs
- Ship wastes off-site
- Decontaminate remaining facilities
- Ship additional wastes off-site
- Conduct long-term site monitoring

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